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RECENT TRENDS IN CONDITION ASSESSMENT OF INDUCTION MOTOR DRIVES

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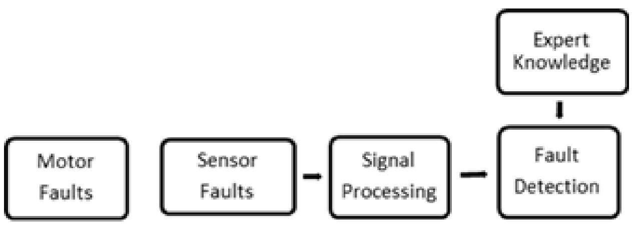
ABSTRACT

The present paper highlights some of the current practices being adopted by technologists and industrialists to pre assess catastrophic faults in an induction motor drive. An overview of modern techniques such as DSP based technique like Fourier transforms, Short time Fourier transform (STFT), Wigner-Ville Distribution (WVD), Wavelet Transforms, Park Vector Technique, Gabor Transforms etc. has been presented in this paper. It has been observed that real time implementation of this process undoubtedly involves expensive tools, yet it is cost effective in the long-run resulting in savings and prevention of electrical drive system faults. The pre-fault warning & timely detection of electric drive system faults also help in prolonged life and reliability of the drive which facilitates reduction of energy and capital loss.

KEYWORDS: Induction Motor, DSP, Fault Detection, Sensors

INTRODUCTION

A large number of Induction motor drives has a direct influence on production in many industrial applications. The Induction motor drives can be energized from constant frequency sinusoidal power supplies or from adjustable frequency, power supplies. However, Induction motors are susceptible to many types of faults, especially when supplied by the variable ac power supplies. This is due to the extra voltage stresses on the stator windings, the resulting induced bearing currents, and the high-frequency stator current components. In addition, motor over voltages can occur because of the length of cable connections between a motor and an ac drive. This fact gave rise to requirement of higher reliability and it has also evoked the research activity in the field of condition monitoring and fault diagnosis of induction machines. Figure 1 shows a block diagram of the general approach to On-line condition monitoring process which takes measurements while a machine is operating, to determine if a fault exists [1]. Starting from the left, common motor faults are shown. Different types of sensors can be used to measure signals to detect these faults. Various signal processing techniques can be applied to the sensor signals to extract particular features which are sensitive to the presence of faults. Finally, in the fault detection stage, a decision needs to be made as to whether a fault exists or not. The results of the 1982 survey [1,2,3] on the reliability of motors in industrial and commercial installations are depicted in the Figure [2].The survey has conducted tests on motors larger than 200H.P. and age not more than 15 years.



Bearings	Vibration	RMS	Model-Based
Stator Winding	Current	Fourier Transform	Trending
Rotor Bar	Magnetic Flux	Time-Frequency	Threshold

Figure 1: Contd.,

Eccentricity	Voltage	Wavelet	Multi-Dimension
		Higher Order Stats	Neural Networks
		Park's Vector	Fuzzy Logic
		Negative Sequence	Expert Systems

Figure 1: The on-Line Condition Monitoring Process

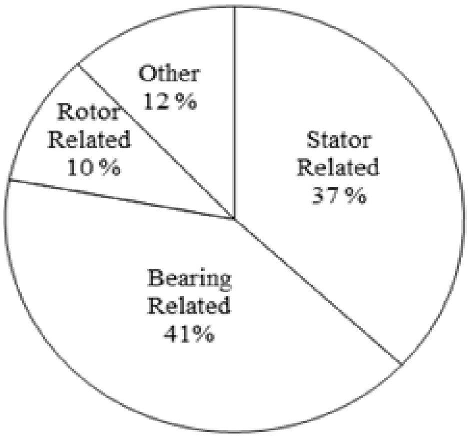


Figure 2: Percentage Failure by Component

INDUCTION MOTOR FAULTS

Bearing Faults

Bearing faults such as outer race, inner race, ball defect and cage defect causes mechanical vibrations which results in air gap eccentricity [4]. These defects have vibration frequency components, 'f_v' that are characteristic of each defect type. Oscillations in air gap length, in turn, cause variations in flux density. The variations in flux density affect the machine inductances, which produce harmonics of the stator current. Figure 3 shows the typical construction of a ball bearing and defines the dimensional parameters used in this paper characteristic current frequencies 'f_{CF}' due to bearing characteristic vibration frequencies are calculate by

$$f_{CF} = \left| f_e \pm m f_v \right|$$

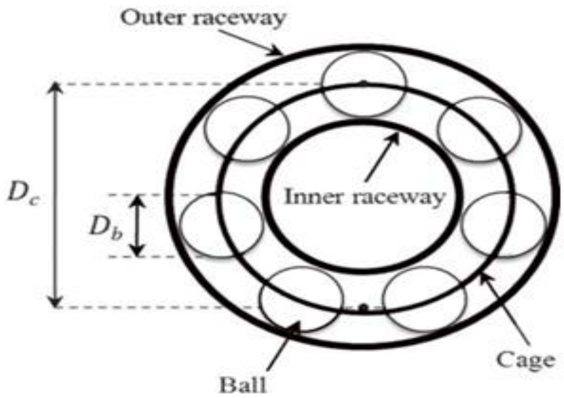


Figure 3: Geometry of Ball Bearing

The characteristic vibration frequencies due to bearing defects can be calculated given that the rotor speed and the bearing dimensions are available. Frequencies due to different defects are given below [5].

$$F_C = \frac{1}{2} F_R \left(1 - \frac{D_b \cos\beta}{D_c} \right)$$

$$F_O = \frac{N_B}{2} F_R \left(1 - \frac{D_b \cos\beta}{D_c} \right)$$

$$F_I = \frac{N_B}{2} F_R \left(1 + \frac{D_b \cos\beta}{D_c} \right)$$

$$F_B = \frac{D_c}{D_b} F_R \left[1 - \left(\frac{D_b \cos\beta}{D_c} \right)^2 \right]$$

Where

F_R = Rotor frequency;

F_C = Cage fault frequency;

F_I = Inner raceway fault frequency;

F_O = Outer raceway fault frequency;

F_B = Ball fault frequency;

D_b = Ball diameter;

D_C = Pitch diameter;

N_B = Number of rolling elements.

β = Ball contact angle.

Percentage Failure Due to Bearing Related Faults are Tabulated Below

Table 1: [1, 2]

Percentage Failure Due to Bearing Related Faults	
Sleeve Bearings	16
Antifriction bearings	8
Seals	6
Thrust bearings	5
Oil leakage	3
Other	3
Total	**41**

Stator Fault

Stator faults accounts for nearly 37 percent of total faults in Induction Motors. The stator windings consist of coils of insulated copper wire placed in stator slots. The stator windings are subject to insulation break-down caused by mechanical vibration, heat, aging, damage during installation and operation etc [6]. Typically short circuits in stator windings occur between turns of one phase, or between turns of two phases or between turns of all phases. Moreover short circuits between winding conductors and the stator core can also occur. This is called turn-to-turn fault or shorted turn fault. This results in extra heating and causes an imbalance in the magnetic field in the Machine. This heat is proportional to square of circulating currents and may lead to complete machine failure if undetected for considerable time. The unbalanced magnetic field can also result in excessive vibrations that can cause premature bearing failures. Percentage failure of Induction Machines due to different components that lead to stator related faults [7]are given in Table-2.

Table 2

Percentage Failure Due to Stator Related Faults	
Ground Insulation	23
Turn Insulation	4
Bracing	3
Wedges	1
Frame	1
Core	1
Other	4
Total	**37**

Rotor Faults

Broken rotor bars can be a serious problem with certain induction motors due to arduous duty cycles. Although broken rotor bars do not initially cause an induction motor to fail, there can be serious secondary effects [8]. The fault mechanism can result in broken parts of the bar hitting the end winding or stator core of a high voltage motor at a high velocity. This can cause serious mechanical damage to the insulation and a consequent winding failure resulting in a costly repair and lost production[9].Broken rotor bars or end rings can be caused by Direct-on-line starting duty cycles, Pulsating mechanical loads, and imperfections in the manufacturing process of the rotor cage. Percentage failure of Induction Machines due to different components that lead to rotor related faults are given in Table-3

Table 3

Percentage Failure Due to Rotor Related Faults	
Cage	5
Shaft	2
Core	1
Other	2
Total	**10**

Other Faults

Other faults accounts for a total of 12 percent of total faults due to external factors beyond the scope of user. Out of 1141 motors surveyed by power systems Reliability subcommittee of the IEEE Industrial Power Systems Department for the survey on the reliability of motors [1, 2], some respondents did not submit adequate data to identify the faults. These unspecified faults are tagged as other faults. These may include eccentricity which occurs when the rotor is not centered within the stator producing a non-uniform air gap between them. This can be caused by defective bearings or manufacturing faults. The variation in air gap disturbs the magnetic field distribution within the motor which produces a net magnetic force on the rotor in the direction of the smallest air gap. This so called “unbalanced magnetic pull” can cause mechanical vibration.

SENSORS

A Sensor is a device that measures a physical quantity and converts it into a signal which can be read by an observer or by an instrument. Presence of any kind of fault in a Induction machine affects its symmetry which in turn change the interaction of flux between the stator and rotor, resulting in changes to the stator currents, voltages, magnetic field and machine vibration. Thus these Sensor signals can be used for on-line condition monitoring. Table 4 classifies the induction motor faults and summaries the detection methods and relevant sensors.

Table 4: Motor Faults and Detection Methods

Group of Faults	Parameter and Detection Method
1) Bearing Faults 40-50% of failures • damaged races, balls, sleeve	-Vibration -stator current spectrum
2) Stator Faults 30-40% of faults • insulation failure related	-axial flux linkage -stator current components and Spectrum -negative sequence currents or impedances detection -partial discharge
3) Rotor Bar/End-Ring Faults 5 to 10% of faults • breakage or cracking of rotor bar or end-ring	- axial flux linkage -stator current spectrum - instantaneous power, torque and speed -vibration
4) Eccentricity • Unequal air gap – static and Dynamic.	- vibration - stator voltage/current vector -current spectrum

Vibration

Vibration monitoring techniques are employed to detect mechanical faults such as bearing faults or mechanical imbalances. A piezo-electric transducer is used which produces a voltage signal proportional to acceleration. Established vibration standards, such as ISO 10186, are then compared to the measured rms vibration level of the machine and are used to detect/warn of possible machinery failures or an unsafe operating condition.

Stator Current

Current signature analysis involves the measurement of electric current around any one phase either through clamp on meters or through CT's. The current signal is conditioned. A/D board digitizes the signal to permit the time and frequency spectra for analysis. The time varying current signal is then transformed into frequency domain through FFT algorithm.

This current is then transformed into its frequency spectra and analyzed for detection of fault.

Axial Magnetic Flux

Due to practical limitations in manufacturing, perfect symmetry cannot be realized in the electric and magnetic circuits of electric machines. Axial leakage fluxes arise because of these asymmetries. By application of Faraday's law, a coil, or any symmetrical arrangement of coils wound around the shaft of the induction machine will detect the axial leakage fluxes. The voltage signals induced in the coils can be processed to get information of induction motor speed, primary and secondary currents, and in the monitoring of machine fault conditions.

Stator Voltage

Stator voltage is measured using a high frequency differential voltage probe or isolation amplifier. It has been used to calculate the instantaneous power, instantaneous torque and negative sequence impedance.

Other Kind of Sensory Parameters

Thermal monitoring, Torque monitoring and Noise monitoring are some of the other techniques that are employed for condition monitoring of induction machines.

A stator current faults generates excessive heat in the shorted turns, and increased bearing wear increases the friction and the temperature in that region of the machine. This increase in temperature of motor can be a detected by thermal monitoring which helps in preventing excessive detoriation of insulation.

Noise and vibration in electric machines are caused by forces which are of magnetic, mechanical and aerodynamic origin. Vibration signal of an electric machine is analysed to detect various types of faults and asymmetries. The major disadvantage of vibration monitoring is cost. It is very costly when compared to other condition monitoring techniques.Cost effective sensor less online vibration monitoring techniques are proposed which are based on the relationship between the current harmonics in the machine and their related vibration harmonics. Partial discharge analysis is also carried out for detecting stator insulation faults in higher voltage motors.

SIGNAL PROCESSING METHODS

Frequency Domain

- Fast Fourier Transforms (FFT)

Time-Frequency Techniques

- Short Time Fourier Transform (STFT)
- Gabor Transform (GT)
- Cohen class distribution
  - Wigner –Ville distribution (WVD)
  - Choi-Williams distribution
  - Cone shaped distribution

Wavelet Transform (WT)

- Discrete Wavelet Transform (DWT)
- Discrete Wavelet Transform (DWT) for Multi resolution Analysis (MRA).

Park’s Vector Approach

Time Series Methods

- Spectral estimation through ARMA models
- Welch method
- Music method
- Periodogram

A comparison has been made between different techniques applied for diagnosis of motor faults in Table 5 as given below:

Table 5: Comparison of Techniques Applied for Diagnosis of Motor Faults

Techniques	Required Measureme-Nt	Faults Diagnosed	Advantages	Disadvantages
FFT	One stator current	•Broken rotor bar fault •Short winding fault •Airgap eccentricity •Bearing faults • Load fault	•Suitable for high load conditions • Easy to implement	• Lost time information • Not effective at light load condition
STFT	One stator current	•Broken rotor bar fault •Short winding fault •Air gap eccentricity •Bearing faults • Load fault	•Suitable for high load conditions • Easy to implement	• Lost time information • Not effective at light load condition
Gabor Transform	One Stator Current	•Short winding Fault	•Fine frequency resolution	•Moderate speed
Wavelet Transform	One Stator Current	•Broken rotor bar fault •Short winding fault	•Suitable for varying load and light load conditions	•Require expertise
Wigner Ville distribution	One Stator Current	•Bearing fault	•Fine frequency resolution •Fast speed	•Strong cross term interference
Park Vector Approach	Three Stator Currents	•Short winding faults •Bearing faults	•Easy to diagnose the fault	•Not effective for load faults and broken rotor bar fault

FAULT INTERPRETATION METHODS

Fault Diagnosis can be a complex reasoning activity, which is currently one of the domains where Artificial Intelligence techniques have been successfully applied.

The reason is that these techniques use association, reasoning and decision making processes as would the human brain in solving diagnostic problems. Fault parameters extracted using the signal processing techniques are now used to decide if a fault exists and if so, what type of fault. Figure 4 shows the flowchart of the fault detection scheme [4].

The process can be divided into three main stages: detection, feature extraction and fault identifier. Experience and knowledge of an expert user is used to distinguish between a healthy and faulty machine. Artificial intelligence and pattern recognition techniques aids in automating the fault interpretation process.

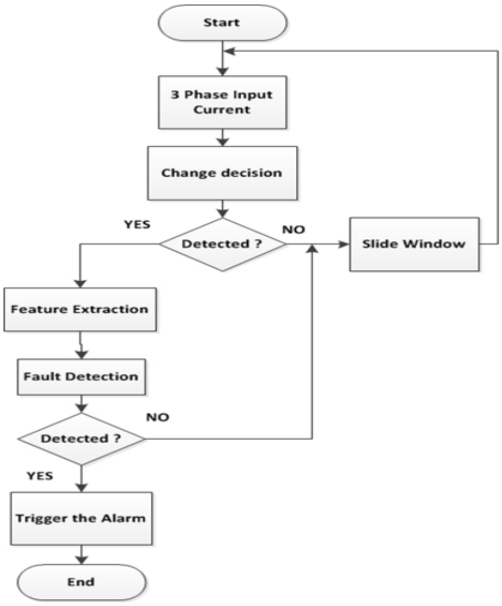


Figure 4: Flowchart of Fault Interpretation Method

Model Based Approach

The effect of particular faults on parameters such as the machine output current can be predicted using analytical or finite-element modeling approaches [10]. These models can allow accurate fault diagnostics for a given machine if detailed electromagnetic machine design information is available. The difficulty with finite element modeling is that it is not a generalized model. In order to analyze faults every motor has to be designed in the software which takes much time and labor.

Artificial Neural Networks

An artificial neural network (ANN), is a mathematical model that is inspired by the structure and/or functional aspects of biological neural networks. A neural network consists of an interconnected group of artificial neurons, and it processes information using a connectionist approach to computation. A artificial neural network model is presented in Figure 5.In most cases an ANN is an adaptive system that changes its structure based on external or internal information that flows through the network during the learning phase [11,12]. They are usually used to model complex relationships between inputs and outputs or to find patterns in data. The training of the neural network is performed by feeding in selected sets of parameters corresponding to known healthy and faulty machines and adjusting the input weights of the neurons to give the required output in each case.

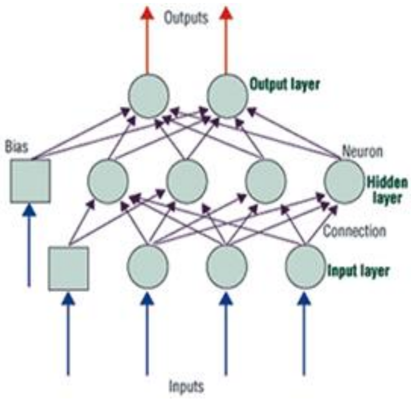


Figure 5: Structure of a Neural Network

Fuzzy Logic

No motor is completely faulty or complete healthy. The motor is said to be faulty or healthy depending on the degree to which faults exists. For instance, based on the broken bar side band amplitude, a motor could be classified as healthy, marginal or faulty. Fuzzy logic allows combining fuzzy information from different signals together to make a more accurate judgment regarding the health of the motor [11,12].

Genetic Algorithm

A genetic or Evolutionary algorithm operates on a group or population of chromosomes at a time, iteratively applying genetically based operators such as crossover and mutation to produce fitter populations containing better solution chromosomes. It is basically a stochastic optimization procedure inspired by natural evolution.

Support Vector Machine

SVMs are the methodologies for creating functions from a set of labeled training data. This function can be a classification function (the output is binary: is the input in a category) or the function can be a general regression function. For classification, SVM operate by finding a hyper surface in the space of possible inputs, which attempts to split the positive examples from the negative examples.

Expert Systems

Experts usually rely on common sense when they solve problems. Expert’s knowledge is represented as a set of rules and from which a conclusion can be drawn. An example of a rule could be: *if* the broken bar sidebands are greater than -45dB*and* the Park's current vector is circular *then* it is likely that a broken bar fault is present [13,14].

FUTURE SCOPE

Use of Multiple Sensor Types

Current practice is to use a single sensor type associated with a particular signal processing technique to monitor the faults in the machine. As Induction Motors are prone to various faults a single sensor is not always reliable. Combining information from multiple sensor types and processing techniques should be integrated to improve the accuracy of fault detection and hence asset management.

Portability of Methods

It is difficult to generalize the results from laboratory testing on what are normally low power machines to the much higher power machines found in the field. For a fault diagnosis system to be practical, it must be applicable to machines with widely different ratings and different construction with little incremental effort [15].

Integrated Online Protection System

The ultimate goal of in electrical machine condition monitoring is an integrated online protection system that is capable of detecting all faults and in addition, being able to estimate fault severity and remaining life.

Generalization of Methods

Generally laboratory tests are done on machines with low power ratings. So, the results obtained in the laboratories may not be applicable to the much higher power machines found in the field. For a fault diagnosis system to be more practical and relevant to industries, it must be applicable to machines with widely different commercial available ratings and different construction with little incremental effort and fruitful outcome of such analysis.

Remote Machine Monitoring

Induction machines equipped in remote sites or in hazardous locations (such as remote mining sites or petroleum processing plants) are not always accessible. It necessitates remote monitoring which may be developed in future.

CONCLUSIONS

The present paper covered an exhaustive detail about several issues concerning fault diagnosis trends for induction motor drives. An overview of current trends in this area has been dealt with necessary implantation software requirements for improving induction motor drive reliability and fault diagnosis. This will enhance asset management strategies of the organization and reduce maintenance cost and hence the production loss.

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